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West-northwest directed obduction of the Batain Group on the eastern Oman continental margin at the Cretaceous-Tertiary boundary

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Abstract. The Batain coast area in eastern Oman is dominated by allochthonous Permian to Late Maastrichtian sedimentary and volcanic rocks (Batain Group), unconformably overlain by neoautochthonous Tertiary sediments. The allochthonous rocks of the Batain coast were previously attributed to the Hawasina complex, the Permian to Coniacian/Santonian sedimentary infill of the neo-Tethyan Hawasina basin off northern Oman. Previous structural interpretations suggested that the Batain Group, along with the Hawasina complex and the Semail ophiolite, was obducted in the Coniacian to Campanian from NE to SW onto the northern Oman continental margin. Results of our work in the Batain area differ from previous interpretations, with most significant differences concerning timing and direction of obduction. Our results show that WNW directed tectonic movements formed a fold-and-thrust belt and led to the obduction of allochthonous rocks onto the east Oman continental margin during latest Maastrichtian/earliest Paleocene times. This is coeval with emplacement of ophiolitic fragments along the eastern coast of Oman (eastern ophiolite belt) but is about 15-20 Myr later than emplacement of Hawasina complex and Semail ophiolite in northern Oman. Postemplacement structural evolution during the Tertiary involved intraplate extension, possibly reflecting the Red Sea/Gulf of Aden opening, and late Tertiary shortening related to convergence between Arabia and Eurasia. Late Tertiary contractional deformation resulted in refolding of the Batain nappes and in folding of the overlying Tertiary sediments. A palinspastic reconstruction of the Batain area indicates that the Permian to Upper Cretaceous sediments were formerly deposited in the Batain basin, a part of the proto-Indian Ocean, along the present-day eastern Oman margin. This leads us to propose that Permian breakup of Gondwanaland created both continental margins of Oman and led to the opening of two major basins: the neo-Tethyan Hawasina basin in the north and the proto-Indian Ocean Batain basin in the east, the latter separating Arabia from greater India.

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1. Introduction

The Batain coast area is situated in northeastern Oman and covers about 4000 square kilometers (Figure 1). It is bounded to the north by the Gulf of Oman and to the east by the Arabian Sea. The Quaternary Wahibah Sands separate the Batain coast area from interior Oman. The area has a low to moderate relief and is dissected by numerous, roughly E-W trending wadis. Recent sand and gravel deposits cover extensive parts of the area. The Batain Plain is dominated by allochthonous Permian to Maastrichtian sedimentary and volcanic rocks. These rocks document the evolution of a basin off the eastern coast of Oman and are referred to as the Batain Group [*Immenhauser et al.*, 1998]. They are unconformably overlain by autochthonous upper Paleocene to Miocene marine and continental sediments. The rocks of the Batain Group were obducted onto the continental margin of Oman, parts of which are exposed near Jabal Ja'alan (Figure 1). Here Precambrian gneisses, migmatites, and schists were intruded by Upper Proterozoic plutonic rocks and dykes [*Roger et al.*, 1991; *Würsten et al.*, 1991] and covered by neoautochthonous Maastrichtian and Tertiary sediments [*Le Métour et al.*, 1995]. On the basis of reflection seismic data, well data, geochemical data, and surface geology, *Beauchamp et al.* [1995] suggested a hidden Cretaceous rift basin (Masirah Graben) underlying the allochthonous sequence of the Batain coast. The Cretaceous rift-related normal faults are believed to have been reactivated in the late Tertiary because of rifting of the Arabian Sea/Gulf of Aden [*Beauchamp et al.*, 1995]

Previous studies interpreted the allochthonous rocks of the Batain Plain as part of the Hawasina complex exposed in the Oman Mountains [*Glennie et al.*, 1974; *Cooper* 1990; *Shackleton et al.*, 1990; *Roger et al.*, 1991; *Béchennec et al.*, 1992; *Wyns et al.*, 1992]. The Hawasina complex represents the Permian to Coniacian/Santonian sedimentary infill of the former neo-Tethyan Hawasina basin. This paleodepositional realm was considered to be located along the northern Oman margin and bounded to the north by a spreading ridge. In the scenario of the authors cited above, the rocks of the Batain Group along with sediments of the Hawasina basin (Hawasina complex) and ophiolites (Semail ophiolites) were thrust toward the SW and obducted onto the northern Oman continental margin during the Coniacian to Campanian at about 85-80 Ma.

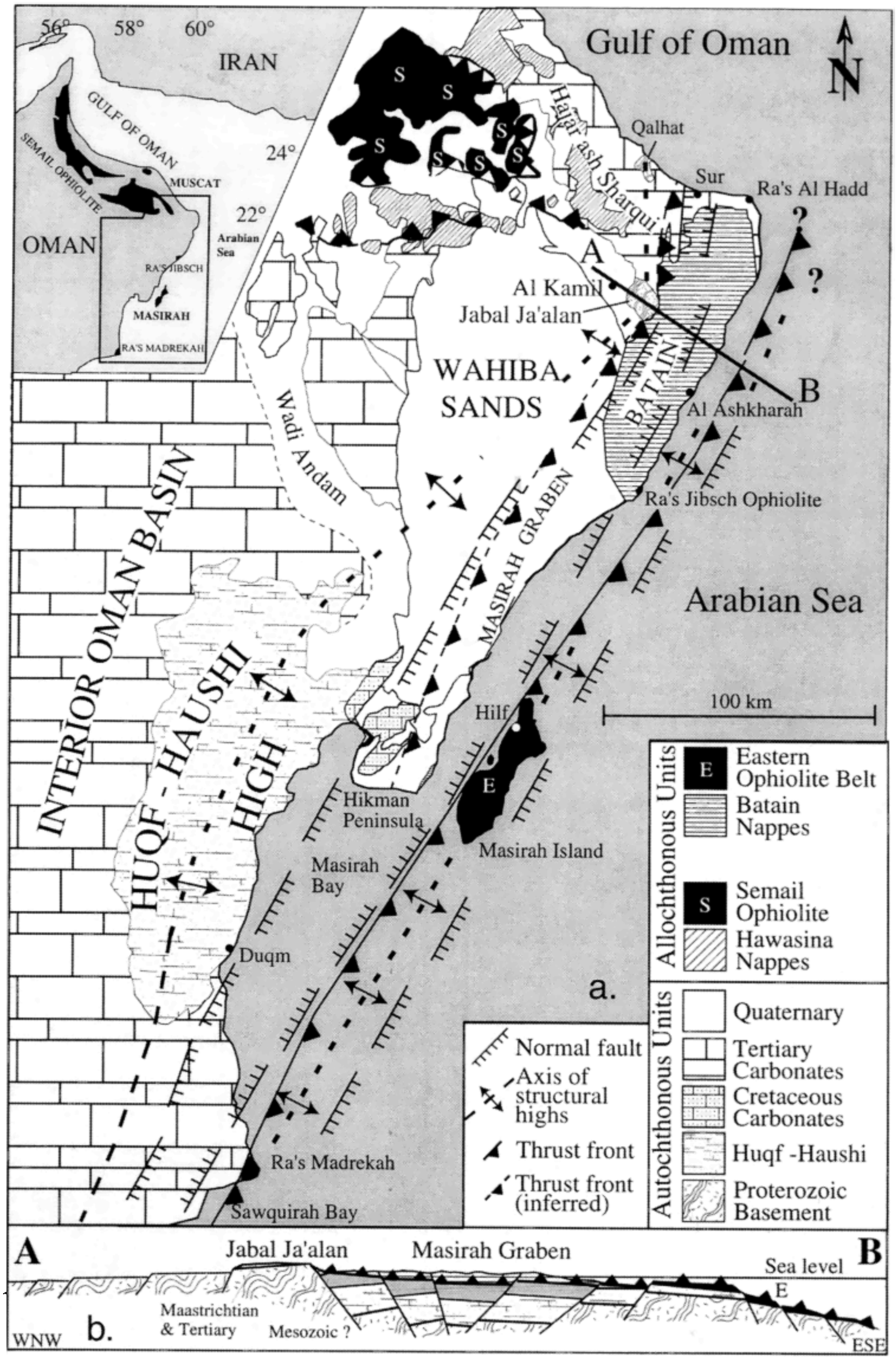

Figure 1. (a) Simplified geological map of northeastern Oman, (b) Schematic section across the Batain area. Location of section is given in Figure 1a.

Ophiolites also build Masirah Island, situated over 100 km to the SSE of the Batain area (Figure 1). The uppermost Jurassic/lowermost Cretaceous Masirah ophiolites, however, formed earlier than the mid-Cretaceous Semail ophiolite in the Oman Mountains [*Beurrier*, 1987; *Immenhauser*, 1995] and were obducted in a NW direction onto the eastern Oman margin [*Immenhauser*, 1995; *Gnos et al.*, 1997; *Peters and Mercolli*, 1997, 1998)]. Paleomagnetic studies of the Masirah ophiolites corroborated these conclusions and ruled out the possibility of a common or related origin with respect to the Semail ophiolite [*Gnos and Perrin*, 1996]. The Masirah Island ophiolites along with other fragments of oceanic lithosphere along the eastern Oman margin (Ra's Madrekah, north of Sawquirah Bay, see Figure 1) were termed the eastern ophiolite belt, and it was postulated that emplacement was related to transpressional motions between the Indo-Pakistani and the Afro-Arabian plates at about 65 Ma [*Gnos et al.*, 1997].

It now became apparent that we should follow up the new data obtained from Masirah Island by investigating the Batain coast area. The stratigraphy, sedimentology, and depositional environment of the Batain Group is discussed in detail by *Immenhauser et al.* [1998]. In the present paper we document results of structural studies in the Batain area, which differ in several aspects from previous structural interpretations. Most significant differences concern timing of obduction and associated tectonic transport direction. Our structural and kinematic findings, supported by biostratigraphic and sedimentologic data [*Immenhauser et al.*, 1998], allow us to propose a new interpretation of the structural evolution of the Batain area and to briefly outline its palinspastic implications.

2. Overview

2.1. Batain Group - Stratigraphic Framework

Establishing the stratigraphy of the Batain Group is complicated by intense folding and faulting. Well-exposed successions with minor to little tectonic disturbance are limited, and sections are generally exposed as thrust slices only. A further complication in setting up a stratigraphic framework is strong lateral facies variations within what is considered one and the same stratigraphic unit. Nevertheless, well-dated sections and careful mapping allow us to establish an overall stratigraphy. New biostratigraphic data were largely obtained from radiolarian-rich lithologies and are reported by *Immenhauser et al.* [1998]. These data were combined with biostratigraphic results of previous studies [*Shackleton et al.*, 1990; *Roger et al.*, 1991; *Béchennec et al.*, 1992; *Wyns et al.*, 1992]. Figure 2 gives an overview of the sedimentary and volcanic rocks in the Batain Group. For reasons of simplicity, stratigraphic nomenclature is largely after *Roger et al.* [1991]; *Béchennec et al.* [1992], and *Wyns et al.* [1992].

The Batain Group consists of (1) the Permian Qarari Formation deposited in the toe of a slope setting; (2) the Upper Permian to Upper Liassic Al Jil Formation comprising periplatform detritus and very coarse breccias; (3) the Scythian to Norian Matbat Formation formed by slope

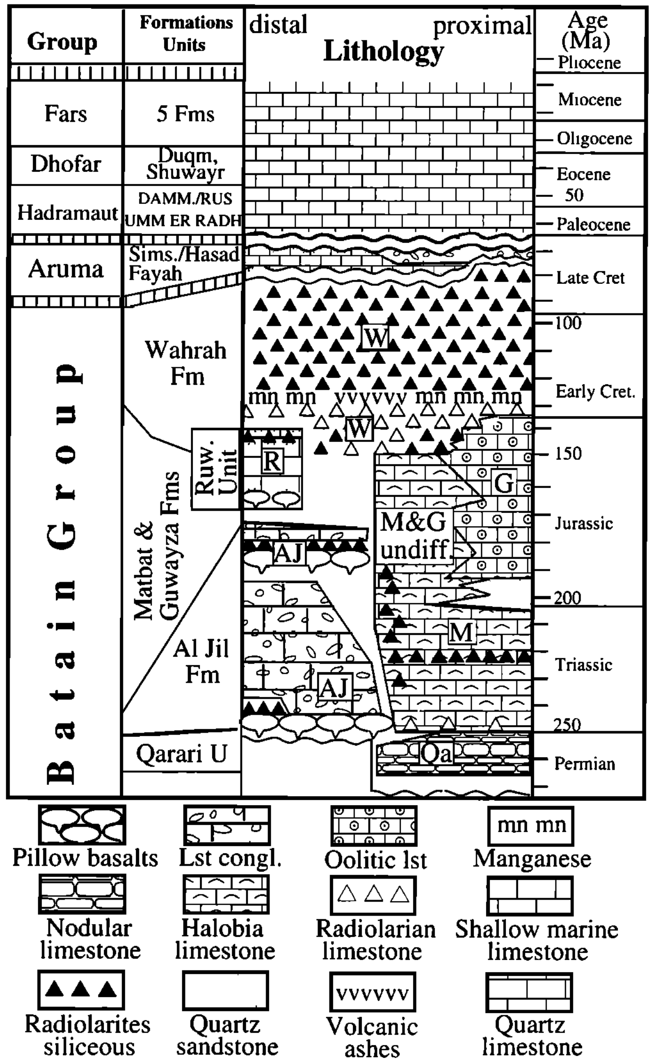

Figure 2. Stratigraphy of the Batain Group and overlying Tertiary sediments.

deposits; (4) the Early Jurassic to Early Oxfordian Guwayza Formation with high-energy platform detritus; (5) the mid-Jurassic to earliest Cretaceous Ruwaydah Formation, interpreted as a fragment of a seamount; (6) the Oxfordian to Coniacian-Santonian Wahrah Formation, mainly radiolarites with locally volcanic intercalations; and (7) the Santonian to uppermost Maastrichtian Fayah Formation built by flysch-type sediments and olistostromes (Table 1). *Immenhauser et al.* [1998] show that the large-scale stratigraphic and sedimentologic pattern found in the allochthonous units exposed in the Batain area is only partly comparable to what was described from the Hamrat Duru Group in the Hawasina complex by *Glennie et al.* [1974] and *Béchennec* [1987]. For more details on the stratigraphic framework of the Batain area the reader is referred to *Immenhauser et al.* [1998]. The Fayah Formation is found along the entire eastern Oman margin but has no equivalent in the Oman Mountains. On Masirah Island the Fayah Formation is sandwiched between ophiolite nappes and contains Coniacian to latest Maastrichtian nannoplankton [*Immenhauser*, 1995, 1996]. It overlies the

Table 1. Summary of Formations and Units Contained Within the Batain Group, Their Depositional Age, Facies and Interpreted Depositional Environment

Formation/ Unit	Depositional Age	Facies	Depositional Environment
Qarari Formation	Permian	argillaceous grey limestones in part on volcanic basement	toe of slope setting below the storm wave base but above the carbonate compensation depth (CCD)
Al Jil Formation	Late Permian to late Liassic	shallow marine calcarenites, conglomerates and megabreccia on pillow basalts and siliceous radiolarites	periplatform detritus and very coarse platform breccias
Matbat Formation	Scythian to Norian	radiolarian limestones and clays overlain by calcarenites, Halobia limestones, shales and siliciclastic carbonates	lower slope setting, possibly reached by heavy storm waves
Guwayza Formation	Early Jurassic to early Oxfordian	graded oolitic calcarenites, fine-grained bio-pelmicrites and calcareous conglomerates	turbidites shed from a high energy platform
Ruwaydah Unit	Mid-Jurassic to earliest Cretaceous	breccias with volcanic and sedimentary clasts, thinly bedded volcanoclastic calcarenites, basaltic and andesitic pillows and flows, radiolarian shales, Ammonitico rosso facies and coarse shallow marine limestone breccias	dismembered seamount structure
Wahrah Formation	Oxfordian to Coniacian/Santonian	radiolarian micrites and clays, "porcellanites" and ribbon cherts	open marine deposits below the CCD, upwelling-radiolarites
Fayah Formation	Coniacian-Santonian to latest Maastrichtian	siliciclastic limestones with derived boulders of continental basement, shales and clays and coarse debris flows	flysch deposits

Ra's Madrekah ophiolite and yields Late Maastrichtian foraminifera [*Gnos et al.*, 1997]. In the Batain area the Fayah Formation ("Fayah Sandstone" of *Shackleton et al.* [1990]) was dated Coniacian to Campanian near Jabal Ja'alan but otherwise was dated Campanian to Maastrichtian by *Shackleton et al.* [1990], Late Maastrichtian by *Béchennec et al.* [1992], and latest Maastrichtian by *Roger et al.* [1991]. The age of the Fayah Formation and the deformation registered in it play an important role in the timing of tectonic events along the east Oman Margin.

2.2. Previous Structural Studies

Structural investigations of the Batain coast area were carried out by *Shackleton et al.* [1990] and by geologists of the Bureau de Recherches Géologiques et Minières (BRGM) as part of their detailed mapping program of Oman, which resulted in the publication of maps NF 40-12, Al Ashkharah with a scale of 1:250,000 [*Béchennec et al.*, 1992], NF 40-08, Sur with a scale of 1:250,000 [*Wyns et al.*, 1992], and NF 40-8E, Ja'alan with a scale of 1:100,000 [*Roger et al.*, 1991] with accompanying explanatory notes. Geologists of the Metal Mining Agency of Japan studied manganese-bearing radiolarites of the Wahrah Formation and their structures in parts of the central and northern Batain area (Metal Mining Agency of Japan, Tokyo, unpublished report, 1982).

Shackleton et al. [1990] described NNE trending, west vergent structures in the southern Batain area (referred to as the Batain fold-and-thrust belt) and mentioned that deformation became increasingly complex northward. Locally, they distinguished earlier structures, which preceded the main NNE trending structures. Most of the Batain coast area, however, was interpreted as a "melange", which was considered to be "primarily tectonic but probably composite in origin" by *Shackleton et al.* [1990]. They considered that the main deformation in the Batain area was of pre-Tertiary and probably pre-Late Maastrichtian age. *Shackleton et al.* [1990] correlated the Batain "melange" with the Hawasina "melange" (Haybi complex sensu *Robertson et al.* [1990] in the Oman Mountains, which structurally underlies the Semail ophiolite. *Shackleton and Ries* [1990] concluded that emplacement of the Batain "melange" and formation of the Batain fold-and-thrust belt were the results of relative plate motions toward the SW during the Late Cretaceous, coeval with the obduction of the Semail ophiolite and the Hawasina complex in northern Oman. They considered Tertiary deformation to be weak. Stronger Tertiary deformation was described near the Jabal Ja'alan Uplift [*Filbrandt et al.*, 1990]. An analysis of Neogene and Quaternary deformation and associated paleostress fields in the eastern Oman Mountains west of Jabal Ja'alan was carried out by *Carbon* [1996], who concluded that deformation since middle-late Miocene times occurred under NE-SW directed compression.

Béchennec et al. ([1992], *Roger et al.* [1991], and *Wyns et al.* [1992] arrived at similar conclusions as *Shackleton et al.* [1990] for the Late Cretaceous deformation event. They also postulated a Late Cretaceous obduction-related deformation event (Coniacian - Early Campanian, i.e., at about 85-80 Ma, their "Eoalpine phase"), which not only affected the Semail ophiolite and the Hawasina complex in northern Oman but also affected Permian to mid-Cretaceous sediments along the Batain coast. *Béchennec et al.* [1992] associated extensive internal deformation in the Upper Jurassic to mid-Cretaceous Wahrah Formation with SW directed obduction. Westward directed thrusting and associated tight N-S to NNE-SSW trending folding in the Maastrichtian Fayah Formation (which in their opinion uncomformably overlies deformed Permian to mid-Cretaceous sediments) was considered by *Béchennec et al.* [1992] to reflect a later phase of WNW-ESE directed tectonic compression during the Late Cretaceous and/or early Tertiary (their "Laramide" phase). Finally, *Béchennec et al.* [1992] mentioned minor open folding, which locally deformed "Laramide phase" thrust sheets and was considered to be of late Miocene age (their "Alpine phase").

3. Structures of the Batain Area

The apparent chaotic and irregular distribution of lithologies in the Batain coast area led *Shackleton et al.* [1990] to propose that most of the area is underlain by a "melange". However, in our opinion there is far more structural coherence than hitherto believed. On the basis of overprinting relationships we distinguish two major contractional events in the Permian to Upper Maastrichtian rocks of the Batain Group, separated from one another by an extensional event. The structural evolution of the allochthonous rocks of the Batain area can be described in terms of obduction-related deformation and postemplacement deformation and is discussed accordingly. Map-scale structural features are shown in Figure 3 along with stereographic plots of major structural elements. Figure 4 gives a more detailed structural overview of the central part of the Batain area.

3.1. Obduction-Related Deformation (First Phase of Shortening)

Surface mapping reveals that a thin-skinned fold-and-thrust belt, building the Batain Group, formed during a first phase of contractional deformation. This phase represents the main deformation event of the Batain Group. It resulted in the most conspicuous structural features along the Batain coast which consist of thin thrust imbricates that generally show intense internal folding. Because of limited vertical relief and lack of continuous outcrop in the Batain coast area, the total thickness of the stacked sedimentary and volcanic rocks is difficult to assess. An estimate of 1.5-2 km for the entire stacked sequence is inferred from seismic sections given by *Beauchamp et al.* [1995]. It is important to emphasize already at this stage that this phase of deformation affects the entire Batain Group, including the Fayah Formation to which *Shackleton et al.* [1990] attributed a Santonian to Maastrichtian age.

The overall trend of the fold-and-thrust belt is roughly NNE-SSW, and the movement direction is WNW to NW (Figures 3 and 4). Deflections of this trend are the result of younger, postemplacement deformation and will be discussed in section 3.2. Deformation style is strongly dependent on mechanical stratigraphy. Structures are best observed in well-layered radiolarian cherts and shales of the Wahrah Formation. First-phase deformation generally produces tight folds whose axial planes are usually moderately to steeply dipping (Figures 3b and 5). Associated thrusts strike parallel to the trend of the fold axes, and their dip is either subhorizontal or subparallel to the dip of the axial plane (Figures 3c and 6). First-phase folds are often asymmetric with a long limb and a steep to overturned short limb. First-phase folds in the Wahrah Formation vary in scale, with amplitudes and wavelengths ranging from 1 m to several hundred meters. Folds in more competent lithologies, such as the siliciclastic and calcareous rocks of the Matbat, Guwayza, and Fayah formations generally have larger amplitudes and wavelengths up to kilometer scale.

Thrust contacts in the Batain fold-and-thrust belt are usually characterized by tectonic breccias and are sometimes associated with occurrences of gypsum. Discrete thrust planes with slickensides have also been observed (Figure 3c). The NW-WNW directed sense of movement on thrusts corresponds to the one inferred from the vergence of asymmetric first-phase folds.

An example of an area dominated by first-phase folding and thrusting is located NNW of Musawa (Figure 7). A tectonic contact dipping 50° to the east and marked by cataclastic deformation separates the Guwayza Formation from sediments of the Wahrah Formation to the west. Younging criteria are ubiquitous in the Guwayza Formation and allow us to classify the large-scale folds as upward facing synclines and anticlines. Fold axes plunge about 35° to north to NNE. Whereas the northern part of Figure 7 is characterized by upward facing folds with subvertical to steeply east dipping axial planes, the southern part shows dominantly overturned asymmetric, west vergent folds.

Figure 8 shows how east dipping thrusts repeat stratigraphic units of the Batain Group in an imbricate stack, each slice having a thickness of about 50-100 m. Internal deformation in the individual thrust slices is especially evident in Wahrah, Matbat, and Guwayza formations. From the WNW vergent folds, the WNW directed facing directions, and the east dipping thrust surfaces, a WNW-directed transport direction is inferred.

On the basis of interpretations of seismic sections, *Beauchamp et al.* [1995] suggested that the allochthonous rocks of the Batain coast are underlain by a low-angle basal detachment at depth. The basal detachment is nowhere exposed at the surface, except on the southeastern flank of Jabal Ja'alan (Figure 4). Here allochthonous rocks of the Batain complex are thrust on top of Maastrichtian slope deposits of the Hasad Formation (age of Hasad Formation after *Roger et al.* [1991]), which represents part of the autochthonous cover of the Jabal Ja'alan Proterozoic basement. The autochthonous Maastrichtian and Tertiary sedimentary cover overlying parts of the Jabal Ja'alan Proterozoic basement is not affected by the intense deformation as seen in the Batain area to the east. This suggests that the exposed basal detachment east of Jabal Ja'alan forms the westernmost limit of the Batain thrust front. The continuation of this thrust front to the north is hidden beneath Tertiary sediments, whereas its southern

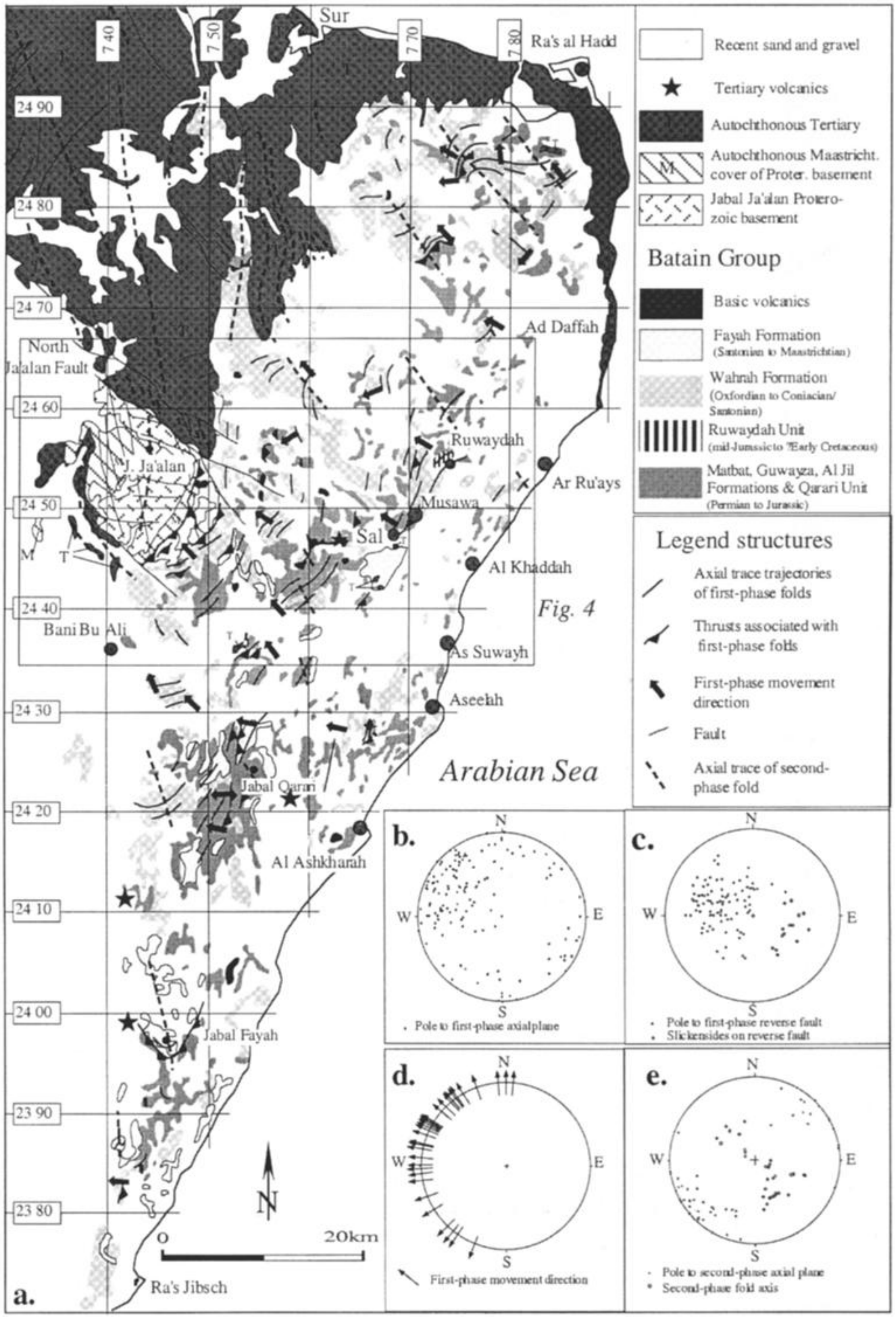

Figure 3. Major structures of the Batain area. Faulting and folding in Jabal Ja'alan area and Tertiary sediments are mainly after *Roger et al.* [1991] and *Béchennec et al.* [1992]. (a) Structural map of the Batain area. (b) Poles to first-phase axial planes. (c) Poles to first-phase reverse faults and orientation of slickensides on these faults. (d) Orientation of first-phase movement directions. (e) Poles to second-phase axial planes and orientation of second-phase fold axes. Structural data are plotted on Schmidt net, lower hemisphere projection.

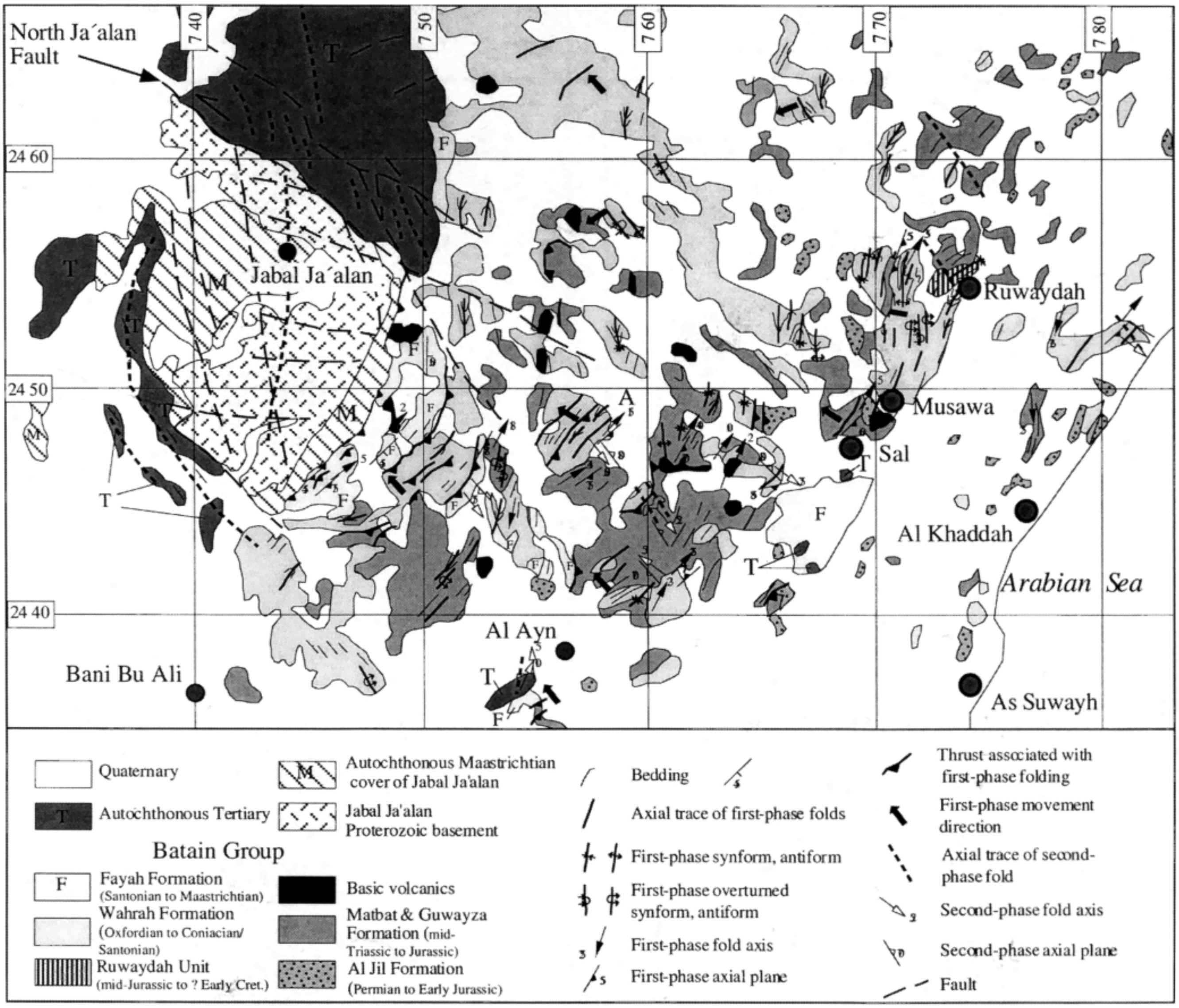

Figure 4. Structural map of the central part of the Batain area. Location of map is given in Figure 3. Structures in Jabal Ja'alan area and Tertiary sediments are mainly after *Roger et al.* [1991].

continuation is covered by the Quaternary Wahiba sands. However, small exposures of the Wahrah Formation (Batain Group) are present in the intertidal zone of the Hikman Peninsula [cf. *Gnos et al.*, 1997, and references therein]. Ophiolites in the southern Batain area (e.g., near Al Ashkharah and about 10 km NE of Jabal Fayah) are as yet undated. They are petrographically different from the Masirah Island ophiolites or the small ophiolitic fragment at Ra's Madrekah forming the eastern ophiolite belt of Oman. The contacts with the surrounding sediments of the Batain Group are not exposed. One possibility is that these ophiolites were accreted during Proterozoic times and now form part of the E-Oman continental basement exposed in a tectonic window and overlain by the basal detachment of the Batain fold-and-thrust belt. Alternatively, the ophiolites could be of Permian or Mesozoic age and form part of the Batain fold-and-thrust belt.

3.2. Postemplacement Deformation

The Batain fold-and-thrust belt was refolded during a second phase of shortening. This phase is less prominent than the earlier phase of intense folding and thrusting. Second-phase folds are generally open and have wavelengths varying between several meters and several kilometers (Figures 3 and 4). The orientation of second-phase fold axes depends on bedding orientation after first-phase folding. Since the overall orientation of bedding is generally moderate to steep because of upright or overturned first-phase folding, second-phase fold axes are mostly moderately to steeply plunging (Figure 3e). The dip of second-phase axial planes is subvertical, and its overall strike varies from NW-SE to NNW-SSE trending in the northern part of the Batain complex to N-S trending in the southern part.

An example of interference structures attributed to superimposition of two folding phases occurs in an area

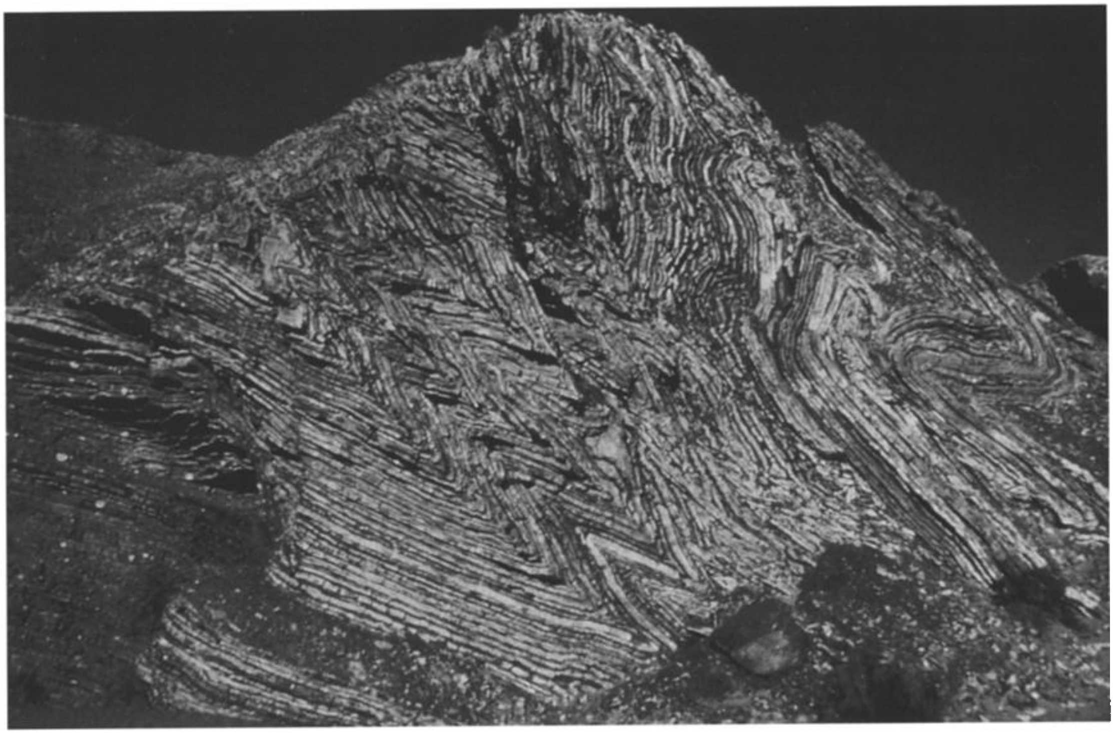

Figure 5. Photograph of latest Maastrichtian/earliest Paleocene chevron-type folds in radiolarian micrites, clays, and ribbon cherts of the Wahrah Formation. Cliff is about 15 m high.

Figure 6. Latest Maastrichtian/earliest Paleocene obduction-related folding and thrusting in rocks of the Wahrah Formation. Inferred movement direction is SW (right-hand side of photograph). Note that this direction is the result of Late Tertiary refolding. Width of photograph is approximately 10 m.

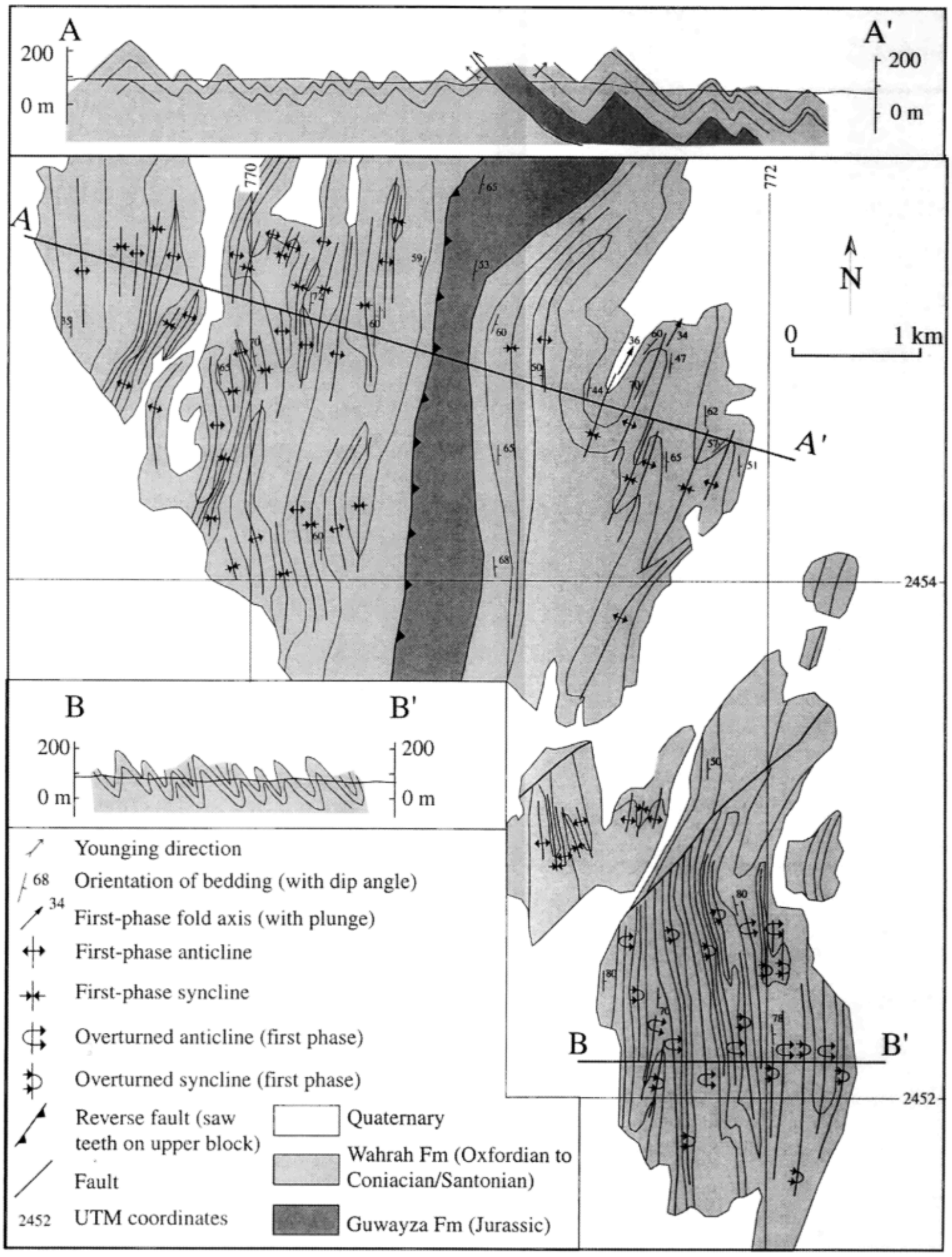

Figure 7. Map showing latest Maastrichtian/earliest Paleocene obduction-related folding and associated thrusting in Wahrah and Guwayza formations. Insets show two cross sections, whose locations are given on the map.

about 10 km WSW of Sal (Figure 9). Here volcanic and sedimentary rocks of the Matbat Formation are thrust on top of rocks of the Wahrah Formation. The contact between the two formations is marked by a tectonic breccia and is deformed by large-scale, second-phase open folding. Fault surfaces dip at about 50° toward the east to SE, and fault striae are roughly downdip toward east to SSE. Deduced movement directions from slickensides are toward the WNW to NW (e.g., at universal transverse mercator (UTM) coordinates 7.59.982/24.45.053). Small-scale west to NW directed thrusts also occur within the Wahrah Formation. Minor parasitic, gentle, second-phase folding in the Wahrah Formation overprints tight to isoclinal first-phase folds (meter to decameter scale), whose overall fold axes azimuths mimic closely the strike of the tectonic contact. First-phase axial planes of tight, west vergent folds are subparallel to the tectonic contact. Within the Matbat Formation, volcanic rocks occur, whose contacts with the surrounding sediments are stratigraphic. These volcanic rocks outline the core of a first-phase, upward facing antiform, which was subsequently

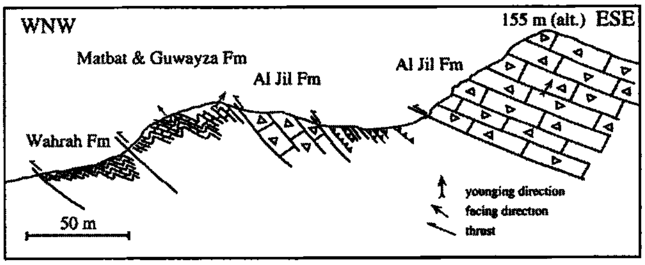

Figure 8. Section showing a stacked sequence of thin imbricates with internal deformation, formed during WNW-ward directed obduction of rocks of the Batain Group. Highest point has universal transverse mercator (UTM) coordinates: 7.66.785/24.28.480.

refolded by open second-phase folds. The latter folds have axial plane traces dipping steeply to the ENE and fold axes generally plunging about 40°-50° toward the SW to SSW.

Another example of first-phase folds overprinted by a second phase occurs in the area of Jabal Fayah (Figure 10). Just south of this hill top, the sediments of the Fayah Formation are deformed by open to tight 50 to 100-m-scale first-phase folds that plunge about 20°-30° to the west. The southernmost visible fold (Figure 10) is overturned toward the north, and its axial plane dips at about 50° to the south.

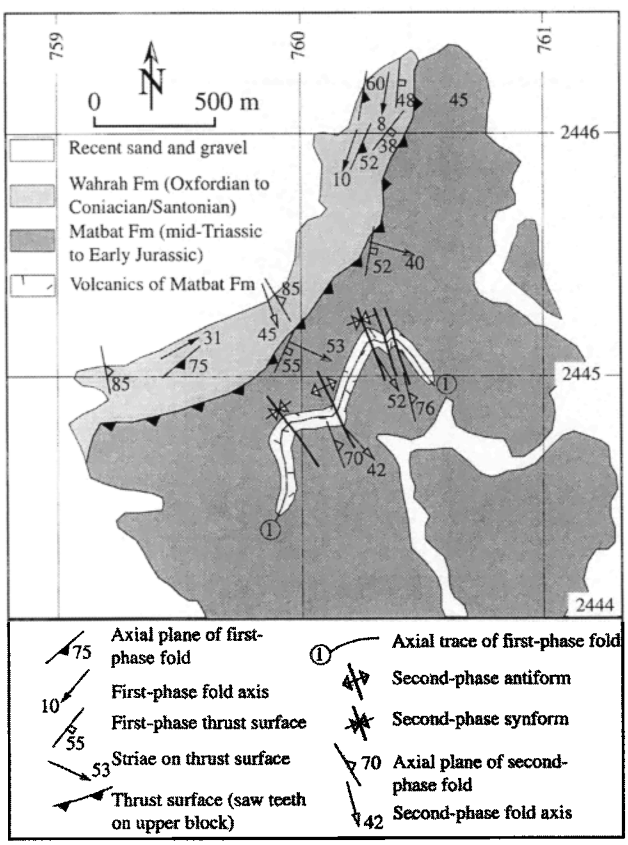

Figure 9. Map of overprinting pattern which is interpreted as the result of superposition of two folding phases, the first straddling the Cretaceous/Paleogene transition and the second during the late Tertiary.

The structural facing of these first-phase folds is upward. These structures are earlier than the large-scale (see schematic inset in Figure 10) open antiform which forms the Fayah Dome [cf. *Shackleton et al.*, 1990] and plunges southward in its southern part. The overprinting relationships are such that on overturned limbs, the structural facing becomes downward with respect to second-phase folding. Similar overprinting relationships occur in other parts of the Batain area, for example near UTM coordinates 7.41.639/23.87.061, where clear younging directions in sediments of the Fayah Formation allow us to distinguish an anticlinal synform and synclinal antiform pair.

The Tertiary sediments of the Batain coast lack the intense first-phase folding and thrusting. Instead, they uncomformably overlie intensely folded and thrusted Permian to Upper Cretaceous sediments and are considered neoautochthonous to these. The Tertiary cover itself is deformed by gentle N-S to NW-SE trending folds (Figure 3), with subhorizontal fold axes and subvertical axial planes. These folds are correlated with similar trending second-phase fold axial traces in the underlying Batain complex. The difference in fold axis plunge can be explained by the pre-second-phase geometric configuration of the strata, that is, intensely folded and thrusted Permian to upper Maastrichtian sediments with steep limbs, overlain by horizontal Tertiary sediments. Folding of such a geometric disposition resulted in the generally steeply plunging second-phase fold axes in the Permian to Maastrichtian sediments and subhorizontal fold axes in the Tertiary cover.

Throughout the entire area, numerous extensional normal faults crosscut the Batain fold-and-thrust belt on outcrop scale. Locally, they occur in conjugate sets. Their orientation is variable because of reorientation by second-phase folding. In areas with minor second-phase overprinting, two sets of conjugate faults can be distinguished: one set is dominant and trends NNE-SSW, whereas the other set trends E-W. Early Tertiary sediments also show evidence for normal faulting, and the extensional phase is therefore placed in Tertiary times, preceding the second phase of shortening. It is

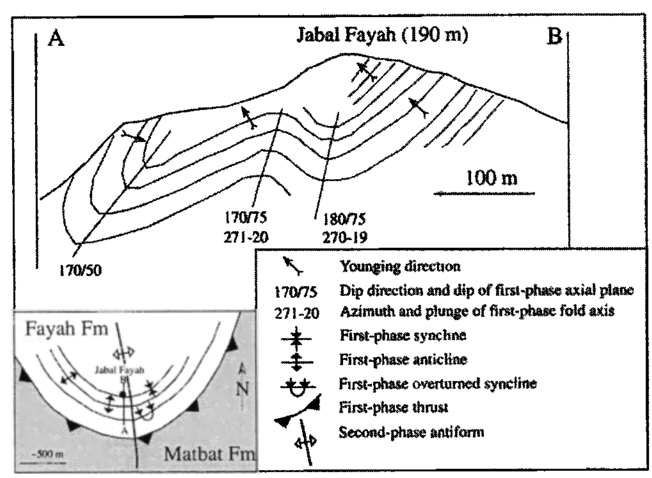

Figure 10. N-S section through Jabal Fayah in the southern part of the Batain area. UTM coordinates of summit of Jabal Fayah are 7.45.725/23.97.200. Inset shows schematically the overprinting pattern in map view.

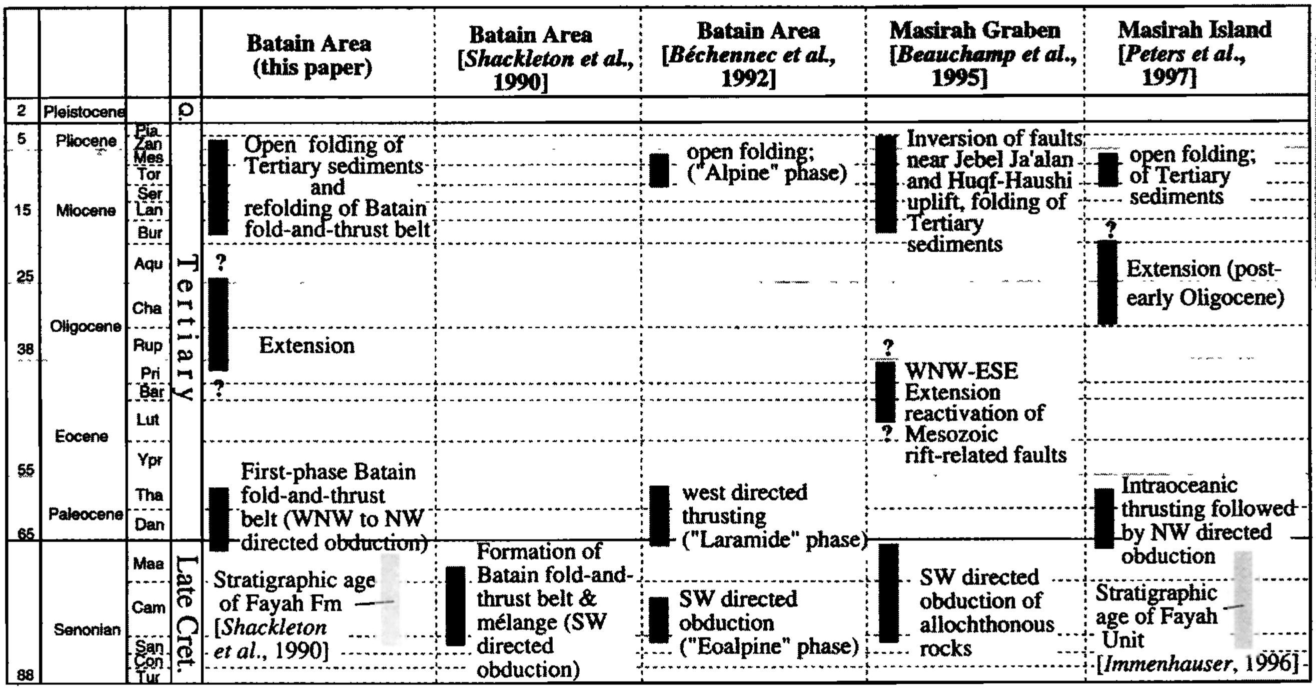

Figure 11. Deformation timetable summarizing the results of our work and comparing it with previous interpretations of Batain coast, Masirah Graben, and Masirah Island.

quite possible that large-scale extensional structures exist in the Batain area as shown for the subsurface by *Beauchamp et al.* [1995]. This, however, cannot be substantiated because of the scattered and discontinuous nature of outcrops.

4. Structures of the Batain Area - Discussion

A summary of the proposed timing of deformation events in the Batain complex is given in Figure 11 along with a comparison to timetables proposed in previous studies.

4.1. Timing of Obduction

During a first phase of deformation the Permian to Upper Cretaceous sediments and basic volcanic rocks of a basin along the Oman continental margin were detached from their oceanic substratum and affected by intense deformation. This deformation resulted in a thin-skinned fold-and-thrust belt and led to the obduction of the Batain Group onto the Oman continental margin. With regard to the timing of emplacement the deformation recorded in the Fayah Formation plays a key role. Equivalents of the Fayah Formation are missing in the Hawasina complex of the Oman Mountains [*Shackleton et al.*, 1990]. On Masirah Island [*Immenhauser*, 1996] and on Ra's Madrekah [*Gnos et al.*, 1997], however, the Fayah Formation has clearly been identified and was attributed a Coniacian/Santonian to late Maastrichtian age [*Immenhauser*, 1995; *Gnos et al.*, 1997]. Deposition of these flysch sediments is considered coeval to the earliest stages of the tectonic phase which ultimately led to the obduction of the eastern ophiolite belt [*Gnos et al.*, 1997].

The Fayah Formation in the Batain area has a Santonian to Late Maastrichtian age [*Shackleton et al.*, 1990]. The sediments of this formation are largely interpreted as flysch deposits, alternating with debris flows and grain flows in a deep water environment [*Immenhauser et al.*, 1998]. The climax of turbidite deposition occurred in Maastrichtian and especially late Maastrichtian times [*Béchennec et al.*, 1992] as manifested by very thick sandstone successions (e.g., at least several hundreds of meters near Jabal Fayah). Chaotic debris flows with decameter blocks (e.g., near Sal, see Figure 3) have also been attributed a Late Maastrichtian age [*Wyns et al.*, 1992]. The continental source of the Fayah Formation is evident from abundant detritic minerals, such as quartz, biotite, and muscovite, and derived pebbles of continental basement. Our structural investigations indicate clearly that the Fayah Formation has undergone the same emplacement-related first-phase deformation as all the other rocks of the Batain Group. This interpretation is fundamentally different with respect to previous authors [*Roger et al.*, 1991; *Béchennec et al.*, 1992; *Wyns et al.* 1992], who suggested that deposition of the Fayah sediments postdates emplacement of other allochthons along the eastern Oman margin.

Emplacement-related deformation is absent in Paleocene and younger deposits. These Tertiary sediments unconformably overlie the Batain Group. This places the age of obduction of the Batain Group on the Oman continental margin in latest Maastrichtian and/or early Paleocene times, that is at about 65 Ma. Obduction is coeval with emplacement of the Masirah ophiolite [*Peters et al.*, 1997], but about 15-20 Ma later than emplacement of the Hawasina complex/Semail ophiolite in the Northern Oman Mountains, which occurred during early Campanian times (82-80 Ma [*Glennie et al.*, 1974]).

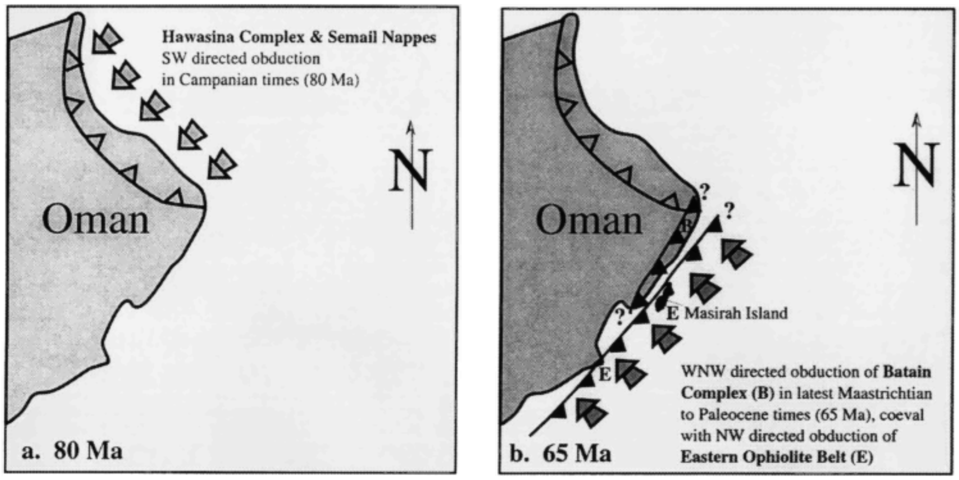

Figure 12. Sketch maps summarizing timing and direction of obduction on the northeastern Arabian peninsula. (a) SW directed obduction of Hawasina complex and Semail ophiolite at 80 Ma. (b) WNW to NW directed obduction of Batain Group and Masirah ophiolite at 65 Ma.

4.2. Direction of obduction

Removing the effects of postnappe Tertiary deformation reveals structures that are characteristic of a thin-skinned fold-and-thrust belt: WNW vergent folds with subhorizontal fold axes and east to SE dipping axial planes, upward to WNW directed structural facing directions and thrust surfaces which are either subhorizontal or subparallel to axial planes and show roughly downdip striae. All structural field criteria point toward the presence of a more or less linear, NNE-SSW trending, fold-and-thrust belt with a WNW directed transport direction. Evidence for an earlier major, SW directed deformation phase in the Batain area as postulated by *Roger et al.* [1991], *Béchennec et al.* [1992], and *Wyns et al.* [1992] is missing. *Shackleton et al.* [1990] also suggested the presence of folds preceding the formation of the Batain fold-and-thrust belt. They underestimated the importance of Tertiary folding, however, and our field work shows that these structures can be explained by Tertiary overprinting of first-phase folds.

Our structural evidence, supported by sedimentologic and biostratigraphic data (presented in detail by *Immenhauser et al.*, [1998]) indicates that emplacement of the sedimentary and volcanic rocks of the Batain Group occurred from approximately ESE to WNW (in present-day coordinates) onto the eastern Oman continental margin (Figure 12).

4.3. Postemplacement Evolution During the Tertiary

The postemplacement Tertiary evolution of the Batain area consisted of an extensional and a contractional event. Extension in the Batain area is evident from numerous mesoscale brittle normal faults which crosscut both the Batain Group and overlying Tertiary sediments. Orientation of conjugate sets of normal faults in areas which have not been reoriented significantly by later shortening are roughly NNE-SSW and E-W and are similar to Tertiary normal faults on Masirah Island [*Marquer et al.*, 1995]. *Beauchamp et al.* [1995] consider that the Cretaceous Masirah Graben, which underlies the Batain fold-and-thrust belt, was reactivated during Tertiary extension. This extension in the Batain area is tentatively linked to extensional intraplate deformation reflecting the Gulf of Aden rifting and progressive opening, which commenced in late Eocene times [e.g., *Beydoun*, 1982; *Hempton*, 1987; *Platel and Roger*, 1989]. Alkali olivine basalts in the Batain area have been dated at 44-37 Ma [*Béchennec et al.*, 1992] and are most likely associated with this rifting event. Mesozoic normal faults associated with the rifting stage along the eastern Oman margin were reactivated during Tertiary extension [*Beauchamp et al.*, 1995] and probably facilitated magma ascent along these deep-seated faults.

The Batain Group was refolded by a later deformation event, which also affected the overlying neoautochthonous Tertiary sedimentary cover to which *Roger et al.* [1991] attributed a late Paleocene to early Miocene age. The NW-SE to N-S trending open second-phase folding thus reflects late Miocene-Pliocene roughly NE-SW to E-W directed shortening. This second phase of shortening (for rocks of the Batain Group) is responsible for the map-scale changes in orientation of first-phase fold axes, axial planes, and movement directions. Neogene shortening is thought to be related to convergence between Arabia and Eurasia [cf. *Hempton*, 1987; *Carbon*, 1996].

Regional changes in the trend of late Miocene fold axial traces might be related to and controlled by major preexisting normal faults. The WNW-ESE trending North Jabal Ja'alan fault is considered a former normal fault, which was reactivated during late Tertiary shortening [*Filbrandt et al.*, 1990; *Carbon*, 1996]. The left-stepping en echelon arrangement of N-S trending folds affecting Tertiary sediments along the North Jabal Ja'alan fault suggests sinistral transpressive movement as already indicated by *Filbrandt et al.* [1990] and by *Carbon* [1996]. Major NNE-SSW trending Mesozoic normal faults underlie the Batain Group [*Beauchamp et al.*, 1995]. These faults are associated with continental extension and breakup leading to the formation of a passive continental margin in east Oman. One of these major normal faults represents the eastern limit of the Jabal Ja'alan uplift and forms the western limit of the Masirah Graben (see section in Figure 1). These normal faults were reactivated during early Tertiary extension [*Beauchamp et al.*, 1995]. It is postulated that NE-SW directed shortening during the late Tertiary would lead to dextral transpressive reactivation of the NNE-SSW trending normal faults and would cause right-stepping en echelon folding, trending roughly N-S, in the immediate vicinity of these former normal faults. Such an overprinting might explain the N-S oriented late folding in the southern Batain coast area. A similar origin is proposed for N-S trending folds affecting Tertiary sediments that have been described farther south on Masirah Island by *Moseley* [1990] and by *Immenhauser* [1995].

5. Summary and Conclusions

On the basis of our structural investigations and combined with sedimentologic and stratigraphic data reported by *Immenhauser et al.* [1998], and published data from the Batain coast and surrounding areas, we present the following major conclusions.

A thin-skinned fold-and-thrust belt (Batain Group) is formed during obduction-related deformation and affects all allochthonous Permian to Upper Maastrichtian rocks in the Batain coast area. Emplacement of the Batain Group onto the Oman passive continental margin occurred during latest Cretaceous and earliest Paleocene times (i.e., at about 65 Ma). This is coeval with obduction of the Masirah ophiolite [*Peters et al.*, 1997] but is much later than emplacement of the Hawasina complex and the overlying Semail ophiolite in the Oman Mountains, which is Early Campanian (82-80 Ma [*Glennie et al.*, 1974]). It is possible that in the northern Batain area, rocks of the Hawasina nappes and/or Semail ophiolite are hidden in the subsurface beneath the Batain Group.

The allochthonous units in the Batain area were obducted from ESE to WNW onto the eastern Oman continental margin (Figure 12). This is in clear contrast to the transport direction of the Hawasina complex and the Semail ophiolite in the Oman Mountains, which is generally inferred as SW directed [e.g. *Glennie et al.*, 1974; *Allemann and Peters*, 1972; *Robertson et al.*, 1990].

The differences in both timing and direction of obduction between the allochthonous units in the Batain coast and those in the Hawasina complex have important palinspastic implications. The paleodepositional realm of the sedimentary and volcanic rocks in the Batain Group was formerly located ESE with respect to the present-day eastern Oman margin. This depositional realm is referred to as the "Batain basin" by *Immenhauser et al.* [1998] in order to distinguish it from the Hawasina basin, whose paleogeographic realm was to the north of the northern Oman margin. Thus the Permian to Upper Cretaceous rocks of the Batain Group were formerly deposited in a basin along eastern Oman that separated the Arabian Plate from greater India. This leads us to propose that the Permian breakup of Gondwanaland created both continental margins of Oman and led to the opening of two major basins: the neo-Tethyan Hawasina basin in the north and the proto-Indian Ocean Batain basin in the east.

Tertiary postemplacement extensional structures are tentatively linked to extensional intraplate deformation reflecting the Gulf of Aden rifting. Late Tertiary, approximately NE-SW directed shortening refolded the Batain fold-and-thrust belt and is most likely related to convergence between Arabia and Eurasia as a consequence of the onset of oceanic seafloor spreading in the Gulf of Aden during the late Miocene. It is suggested that basement anisotropies created during Permo-Mesozoic and/or Tertiary extension exerted an important control on late Tertiary fold orientations. Major preexisting normal faults are believed to have been reactivated during transpression in late Tertiary times.

The intense obduction-related deformation followed by postemplacement deformation overprinted an already complex paleogeographic realm [cf. *Immenhauser et al.*, 1998]. This resulted locally in apparently irregular, disjointed, and chaotic structures, especially in areas where continuous outcrop is lacking. However, there is far more structural coherence in the Batain area than previously documented and we feel that the term "melange" as suggested by *Shackleton et al.* [1990] for the Batain coast should be abandoned.

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